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FURTHER STUDIES ON DYNAMIC CRACK CURVING

by

Y.-J. Sun, M. Ramulu, A. S. Kobayashi and B. S.-J. Kang

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FURTHER STUDIES ON DYNAMIC CRACK CURVING

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The elasto-dynamic stress field surrounding rapidly propagating cracks in thin polycarbonate, double edged crack tension specimens were analyzed by dynamic photoelasticity using a 16-spark gap Cranz-Schardin camera system. Crack curving was observed in two slanted double edged crack specimens and in two offset parallel double edged crack specimens. In another test, the crack ran straight between two symmetrically located twin cracks. Results of these five tests were used to verify the dynamic crack curving criterion by Ramulu et al. in which a reference distance of

$$r_0 = 1/128 \pi [K_I / \sigma_{max} V(c, c_1, c_2)]^{** 2}$$

from the crack tip is incorporated into the maximum circumferential stress or minimum strain energy density criteria. The critical material property for crack curving in this thin polycarbonate sheet was found to be about $r_c = 0.5$ mm.

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INTRODUCTION

In a paper in 1963, Erdogan and Sih [1] used the orientation of maximum circumferential stress to predict crack extension of inclined cracks in tension specimens. This mixed mode crack extension criterion, commonly referred to as the maximum circumferential stress criterion, was later advanced among others by Williams and Ewing [2] and Finnie and Saith [3]. More recently, Streit and Finnie [4] incorporated the second order term, $\sigma_{\theta\theta}$, in the crack tip stress field and proposed a crack curving criterion based on the directional stability of a mode I crack propagation. This stability criterion introduced another critical material parameter, r_c , which is the radial distance from the crack tip. The second order term of $\sigma_{\theta\theta}$ was also used by Cotterell and Rice [5] for predicting the crack curving direction of a slightly curved crack. Historically, Yoffe was the first to use the maximum circumferential stress theory to explain surface roughening and crack branching of a rapidly propagating crack in 1951 [6].

As a natural extension of Griffith's energy release rate, Hussain et al. [7], Palaniswamy and Knauss [8] among others predicted the direction of crack kinking based on the maximum energy release criterion. Focusing directly on energy, Sih [9] predicted that the crack would kink in the direction of the minimum strain energy density factor, S . In an early critique of 1976, Swedlow [10] concluded that the difference between the crack kinking angle predicted by the maximum circumferential stress criterion and the minimum strain energy density criterion "are modest at most". Theocaris and Andrianopolous [11] recently modified the S theory and designated the mean value of S , a critical material value for crack extension. Sih [12] also applied the minimum S theory to predict crack kinking of a dynamic crack.

Ramulu et al., in a recent paper [13], incorporated the second order term of $\sigma_{\theta\theta}$ in the dynamic crack tip stress field and then derived the dynamic counterpart of the crack stability model based on the maximum circumferential stress criterion as well as the minimum strain energy density factor. This dynamic crack curving criterion was used to evaluate nine dynamic photoelasticity tests involving curved as well as straight propagating cracks in fracturing Homalite-100 specimens. The critical material property of r_c was found to be 1.3 mm for the Homalite-100 specimens investigated. More importantly, the crack curving directions predicted by either the maximum circumferential stress theory or the minimum strain energy density theory were generally within 1 degree of each other for the relatively low crack velocities observed in these tests. The sign of $\sigma_{\theta\theta}$ was also found to influence significantly the crack angle of a running crack. The purpose of this paper is to provide further evidence in support of the dynamic crack curving criterion advanced by Ramulu et al.

DYNAMIC CRACK CURVING CRITERIA

Maximum Circumferential Stress Criterion

The maximum circumferential stress criterion, as modified by Ramulu et al. [13], assumes that the crack will extend towards the maximum circumferential stress which reached its critical value at a critical distance, r_c , away from the rapidly propagating crack tip. r_c is a characteristic distance derivable from the crack stability criterion

involving the second order term of σ_{max} in the dynamic crack tip stress field. This characteristic distance is [13].

$$r_0 = 1/128/\pi * [K_I / \sigma_{\text{max}} * V(c, c_1, c_2)]^{**2}$$

where K_I is the dynamic stress intensity factor.

σ_{max} is the second order term in the dynamic stress field and is often referred to as the remote stress component.

c , c_1 and c_2 are the crack velocity, dilatational wave velocity and the shear wave velocity, respectively.

$V(c, c_1, c_2)$ is the dynamic correction factor to the static crack instability criterion and is given in Reference [13].

This crack curving criterion which is the dynamic extension of that by Streit and Finnie [3] can be used to predict the crack curving of a crack propagating under pure mode I as well as mixed mode, i.e. modes I and II, conditions.

Minimum Strain Energy Density Criterion

The minimum strain energy density criterion, as modified by Ramulu et al. [13], also incorporates the characteristic distance of r_0 and thus the second order term of σ_{max} in the strain energy density factor, S , of Sih [9]. Unlike the maximum circumferential stress criterion, the minimum S condition yields a relation between the crack curving angle and r_0 in terms of the given σ_{max} and modes I and II stress intensity factors, K_I and K_{II} . Given r_0 , however, the extended minimum strain energy density criterion with the σ_{max} term can be used to predict crack curving of a mode I static crack or a crack propagating at a low crack velocity.

Homalite-100 Fracture Specimens

The validity of the above two dynamic crack curving criteria were assessed through re-evaluated dynamic photoelasticity results of Homalite-100 fracture specimens [14-18]. r_0 for the minimum S criterion was equated to r_c which was found to be about 1.3 mm for the Homalite-100 data used in evaluating the maximum circumferential stress criterion. For the relatively low crack curving angles of -20 to 25 degrees observed in the nine tests, both the maximum circumferential stress and the minimum strain energy density criteria predicted the fracture angles within 1 degree for most of the 81 data points considered in this investigation [13].

POLYCARBONATE FRACTURE SPECIMENS

In order to further verify the above dynamic crack curving criteria, a series of dynamic photoelastic fracture experiments involving thin polycarbonate fracture experiments were conducted. Specimen configurations and the crack paths in five double edged crack tension specimens with either offset parallel cracks, offset slanted cracks and symmetrically located twin cracks, used in this investigation are shown in Figure 1. The annealed thin polycarbonate specimens with blunt starter cracks exhibited brittle fracture with shear lips less than 10 percent of the thickness and an apparent crack tip yield zone of less than 1.5 mm. The dynamic isochromatics surrounding the propagating crack were recorded with a 16 spark gap Craz-Schardin Camera System.

The isochromatic data were reduced by least square fitting to the recorded dynamic isochromatics a theoretical mixed-mode, dynamic crack tip stress field with disposable parameters of K_I , K_{II} and σ_{max} [19]. The characteristic crack tip distance, r_0 , was then computed by Equation (1). With r_0 known, the predicted crack curving angle can be computed by the maximizing condition for the maximum circumferential stress criterion or the minimizing condition for the minimum S criterion. Details of this data reduction procedure can be found in Reference [20].

RESULTS

As shown in Figure 1, crack always propagated from the longer left crack and curved towards the shorter stationary right crack except for Specimen S2-810519 which involved a symmetrically located twin crack. Also the eccentric loading of Specimens S15-810727 and the longer initial crack length of Specimen S5-810530 caused the rapidly propagating upper crack to intersect with the stationary lower crack at its midcrack length.

Figure 2 shows two typical dynamic isochromatic patterns in a fracturing offset, slanted, double edged crack tension specimen. The right edge crack did not propagate during the entire fracture event. Both frames in Figure 2 show the expanding shear wave front which emanated from the original crack tip of the left edged crack when it started to propagate. Figure 3 shows the variations in K_I , K_{II} , σ_{max} and crack velocity of the upper crack in Figure 2. While the crack velocity and K_I remained essentially constant through the relatively straight propagation of the upper crack, σ_{max} oscillated consistent with previous observations [13].

Figure 4 shows two typical dynamic isochromatic patterns in a fracturing offset, parallel double edged crack specimen. Although the upper crack had cut the specimen in half, the stationary lower crack continued to show a high mode II crack tip stress field in Frame No. 10 of this figure. A similar high mode II crack tip stress field was observed in all stationary cracks during the latter part of crack propagation history. Figure 5 shows the variations in K_I , K_{II} , σ_{max} and crack velocity of the upper crack in Figure 4. The larger excursion in K_I in this figure is associated with the curved crack shown in Figure 4. Figure 6 shows the K_I , K_{II} and σ_{max} of the lower stationary crack in Figure 4. While $K_I = 3 \text{ MPa}\sqrt{\text{m}}$ of this crack was close to the estimated fracture toughness of polycarbonate, the small difference in the crack tip bluntness probably prevented crack propagation of the lower right crack. K_{II} of the stationary crack varied from -8.5 to $0.6 \text{ MPa}\sqrt{\text{m}}$ and is about half of the K_I value. This high value, not commonly observed in previous dynamic photoelastic experiments, is due to the load redistribution caused by the decreasing remaining ligament in the fracturing specimen.

Figure 7 shows typical isochromatics of an edge crack propagating between two symmetrically located twin cracks. High mode II crack tip stress fields are noted in the stationary twin cracks in Frame No. 12 of this figure. Figure 8 shows the variations in K_I , K_{II} , σ_{max} and crack velocity of the propagating left crack. Oscillations in σ_{max} are smaller in this straight crack which is propagating at approximately the same crack velocity of $0.2 \cdot c_1$ as the other cracks.

Figure 9 shows the variations in characteristic distance, r_0 , which was computed by Equation (1), for the propagating cracks in the five tests. r_0 for the curved portion of the rapidly propagating crack is larger than the r_0 of the straight crack. Also r_0 , within the scatter band indicated in Figure 9, always dropped to a minimum value at the onset of crack curving. The

scatter band of the minimum value of r_0 yield an average $r_c=0.5$ mm. This value is consistent with the r_c value estimated by Theocaris [21].

Having estimated the r_c for this thin polycarbonate fracture specimens, the crack curving angle was then estimated either by using the maximum circumferential stress or the minimum S criteria. The results, as summarized in Table 1, show that the predicted and experimentally observed crack curving angles for these five tests were mostly within 1 degree of each other regardless of the crack curving criterion used.

CONCLUSIONS

1. Dynamic crack curving angle under pure mode I and mixed mode I and II conditions can be predicted by using either the extended maximum circumferential stress or the minimum strain energy density criteria.
2. The critical characteristic crack tip distance is $r_c=0.5$ mm for the thin polycarbonate fracture specimens considered in this investigation.

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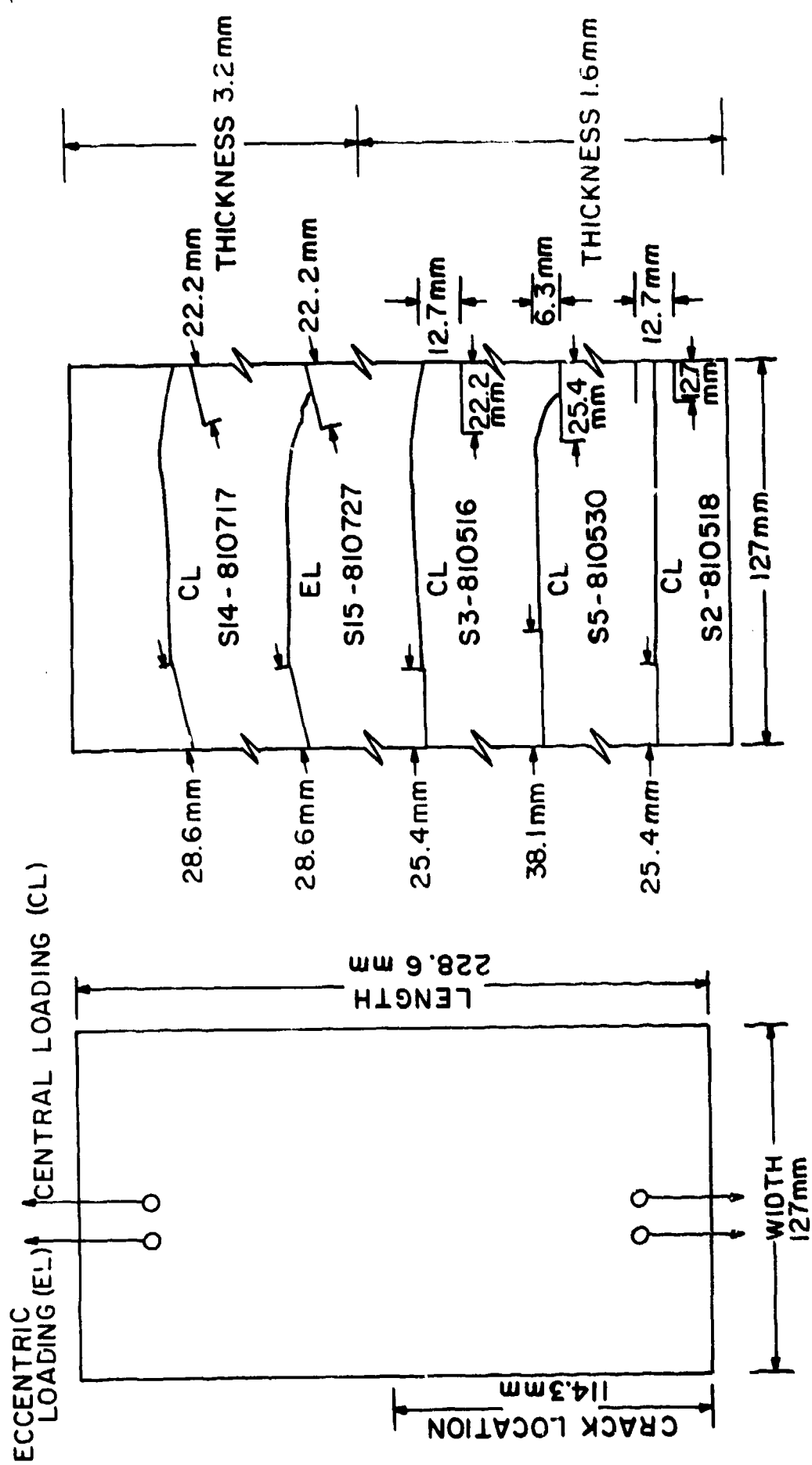
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TABLE 1

SUMMARY OF EXPERIMENTAL AND THEORETICAL RESULTS

Total Number of Experiments:	5
Type of Fracture Specimens:	Double Edged Crack Specimen
Number of Data Points:	114
Crack Velocity, c/c_I :	About 0.2
K_I (MPa \sqrt{m}):	1.5 to 3.2
K_{II} (MPa \sqrt{m}):	-0.5 to 0.6
σ_{max}/K_I :	-11.1 to 2.5
r_0 (mm):	0.25 to 0.75
Measured Crack Curving Angle:	-20 to 3 degrees
Predicted Crack Curving Angle:	
Maximum Circumferential Stress:	-19 to 5 degrees
Minimum S:	-18 to 5 degrees



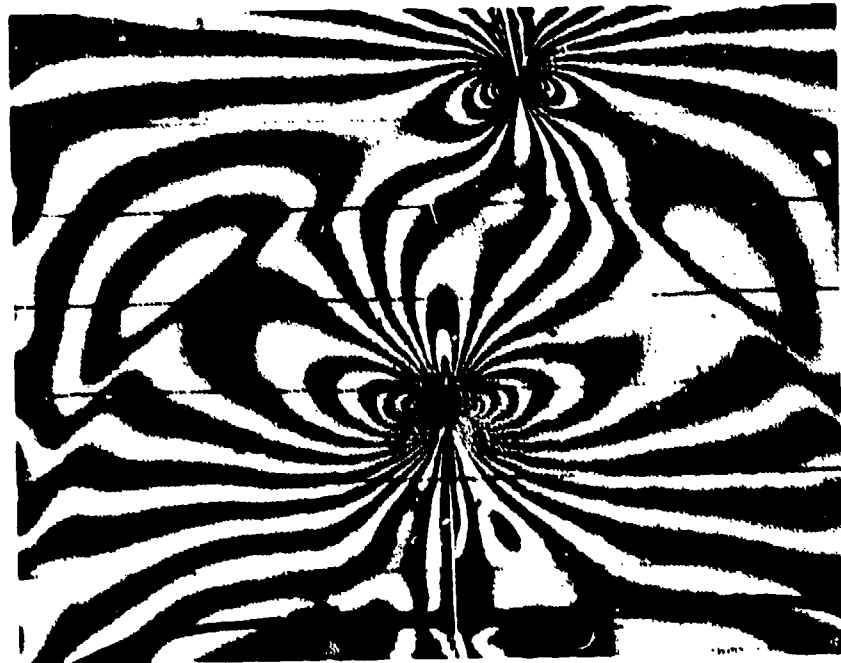
(a) SPECIMEN DIMENSIONS

(b) CRACK PATHS

FIG. 1. POLYCARBONATE DOUBLE EDGED CRACK TENSION SPECIMEN.



FIRST FRAME
6 μ SECONDS



SEVENTH FRAME
28 μ SECONDS

FIG. 2. TYPICAL DYNAMIC PHOTOELASTIC PATTERNS IN POLYCARBONATE SLANTED
DOUBLE EDGED CRACK TENSION SPECIMEN. SPECIMEN NO. S14-810717.

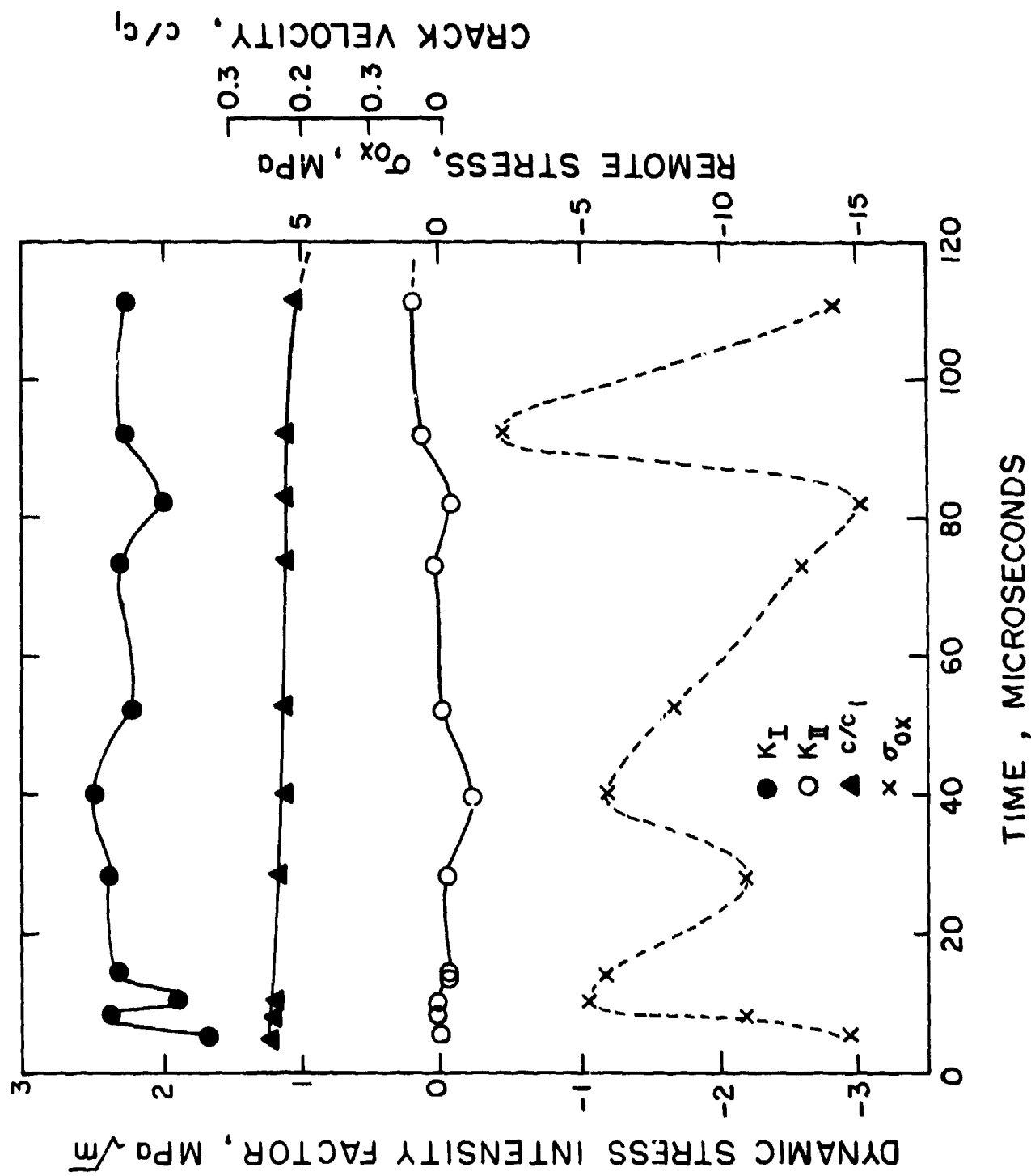
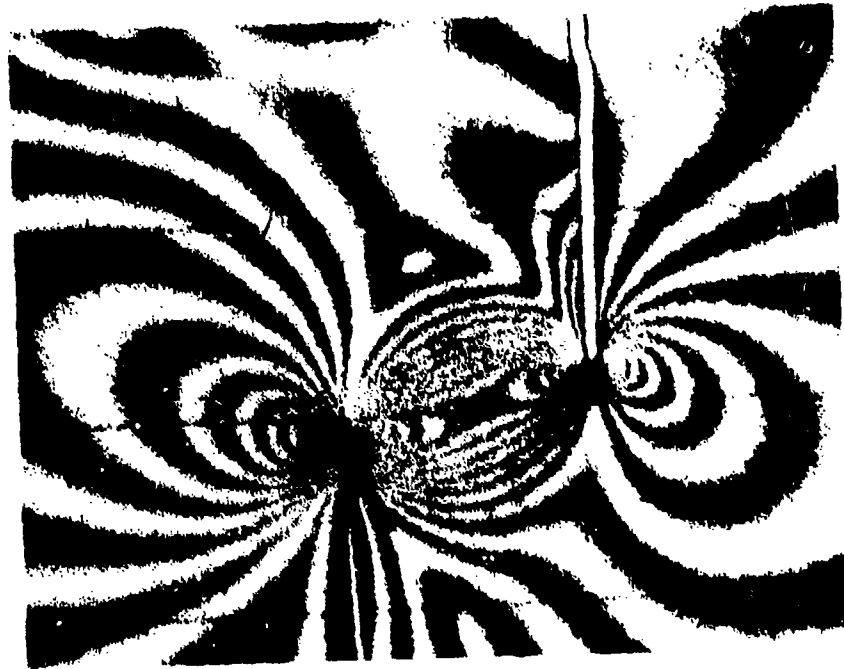
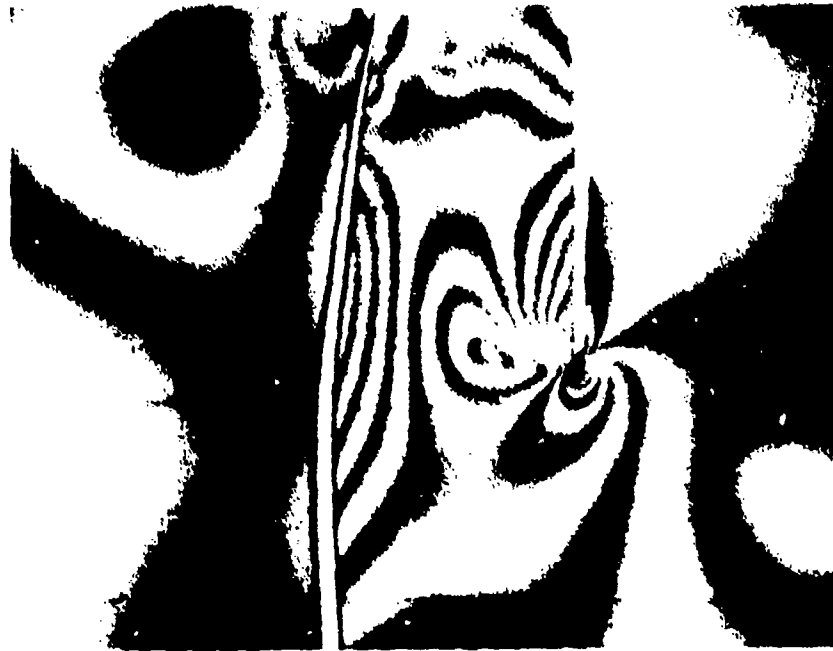


FIG. 3. DYNAMIC STRESS INTENSITY FACTOR, CRACK VELOCITY AND σ_{ox} OF UPPER CRACK OF SPECIMEN NO. S14-810717.



SEVENTH FRAME
150 μ SECONDS



TENTH FRAME
225 μ SECONDS

FIG. 4. TYPICAL DYNAMIC ISOCHROMATICS OF A CURVED CRACK IN A POLYCARBONATE PARALLEL DOUBLE EDGED OFFSET CRACK TENSION SPECIMEN. SPECIMEN NO. S3-810526.

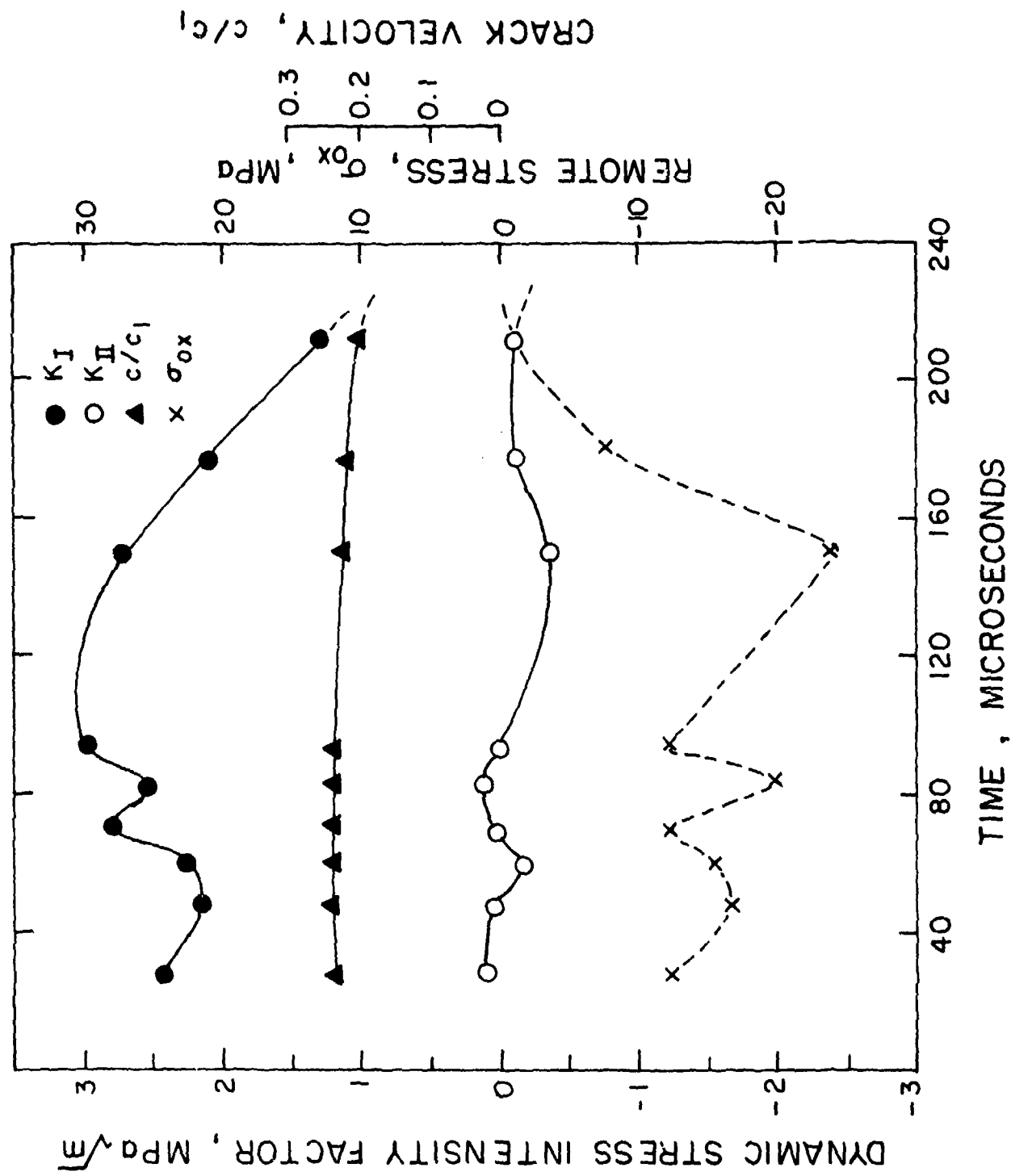


FIG. 5. DYNAMIC STRESS INTENSITY FACTOR CRACK VELOCITY AND σ_{ox} OF UPPER CRACK OF SPECIMEN NO. S3-810526.

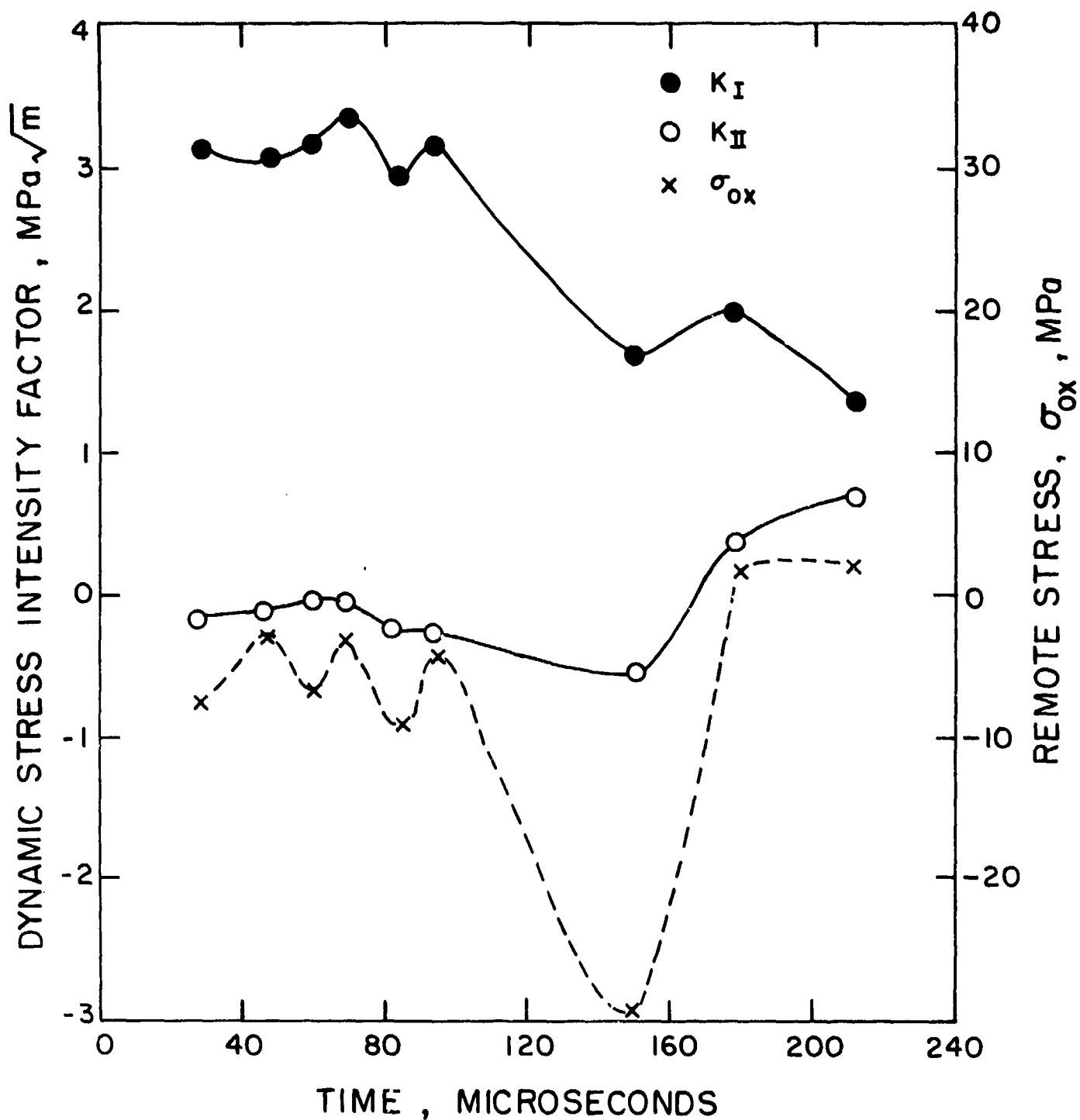


FIG. 6. DYNAMIC STRESS INTENSITY FACTOR AND σ_{ox} OF THE STATIONARY LOWER CRACK OF SPECIMEN NO. S3-810526.



SIXTH FRAME
100 μ SECONDS



TWELFTH FRAME
262 μ SECONDS

FIG. 7. TYPICAL DYNAMIC ISOCHROMATICS OF A STRAIGHT CRACK PASSING THROUGH SYMMETRICALLY LOCATED TWIN CRACKS. SPECIMEN NO. S2-810518.

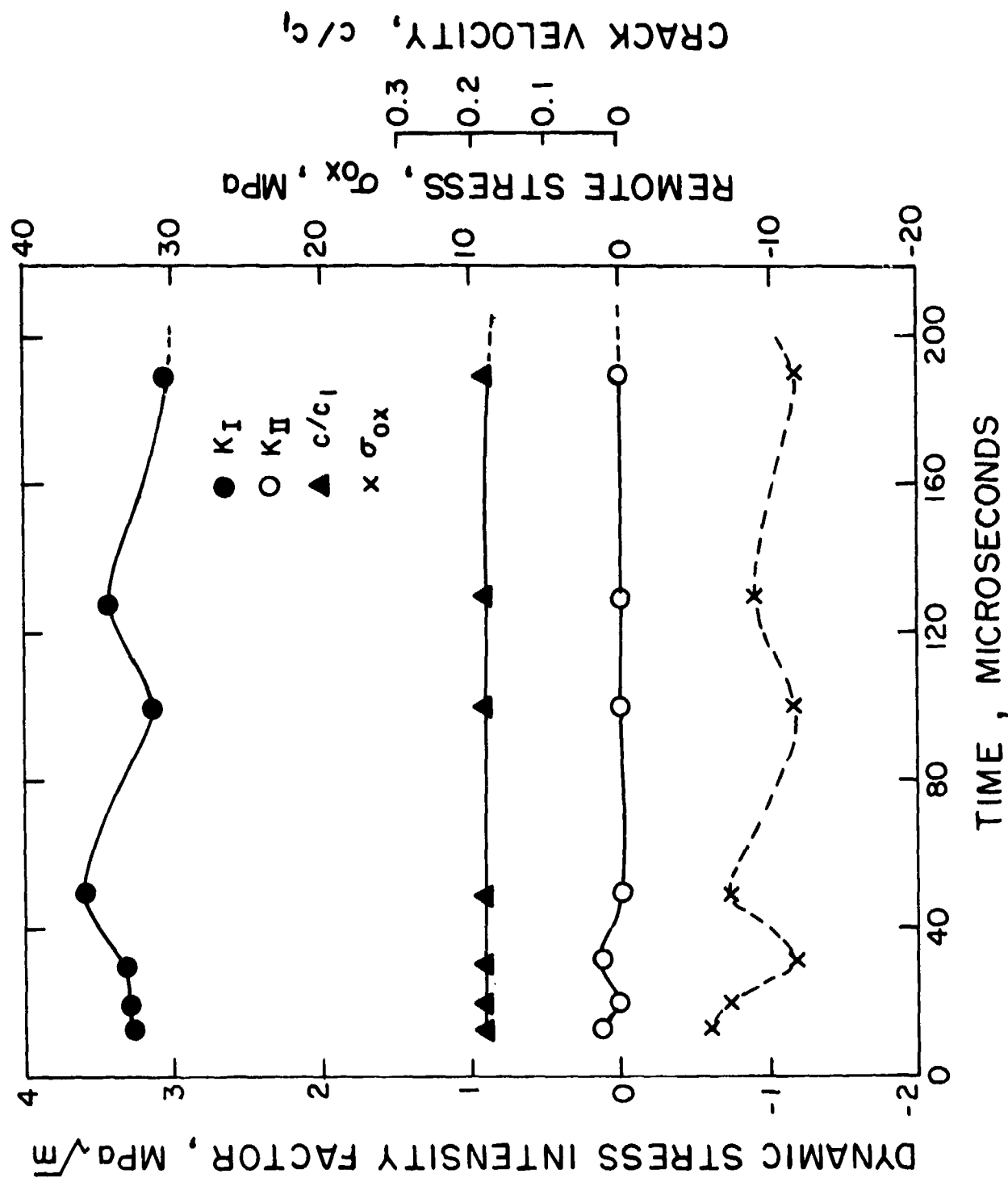


FIG. 8 . DYNAMIC STRESS INTENSITY FACTORS, CRACK VELOCITY AND σ_{ox} OF THE RUNNING CRACK OF SPECIMEN NO. S2-810518.

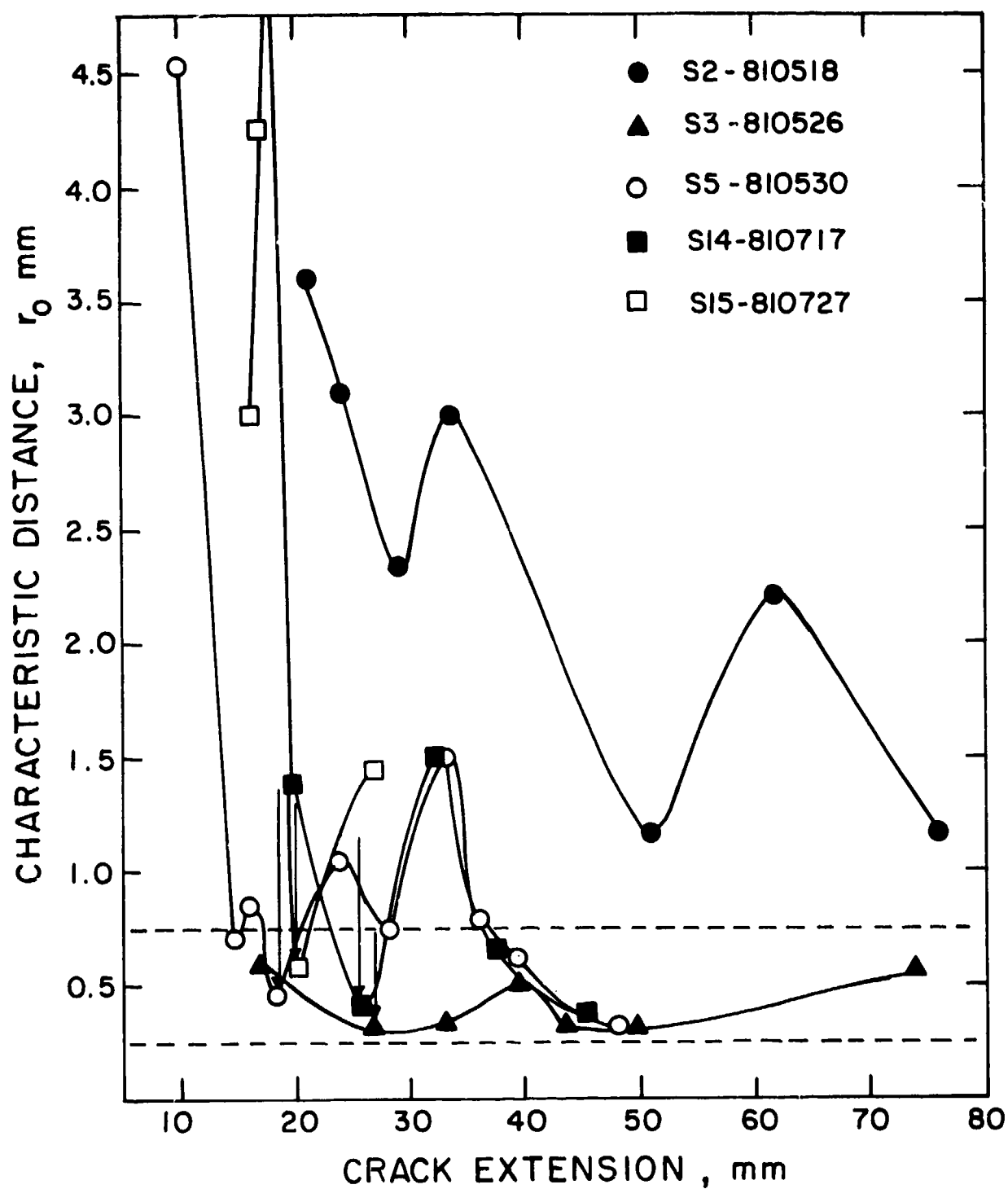


FIG.9. CHARACTERISTIC DISTANCE r_0 OF PROPAGATING CRACK IN THE POLYCARBONATE DOUBLE EDGED CRACK TENSION SPECIMENS.

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is incorporated into the maximum circumferential stress of minimum strain energy density criteris. The critical material property for crack curving in this thin polycarbonate sheet was found to be about $r_0 = 0.5$ mm.

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